ADVANCEMENTS IN FLEXIBLE CIGS MODULE MANUFACTURING

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ABSTRACT

Roll-to-roll (RTR) manufacturing of consistent photovoltaic (PV) material over 1000-ft long metal foil lots has been realized at Global Solar Energy (GSE). Development of robust sensors and *in-situ*, real-time process control strategies for all thin-film coating (TFC) steps has enabled Global Solar to achieve manufacturing yields above 90%. In turn, reliable processing conditions enable rapid progress using well-controlled experiments designed for device optimization. Average large-area cell efficiency now exceeds 10%. Efficiency and yield have also been increased at the module level through improved fabrication methods. Flexible modules attain a power-to-weight ratio of 40W/kg and aperture area efficiencies exceeding 11%. Real-time and accelerated stress tests investigating product reliability are underway.

INTRODUCTION

Besides the use of compact, relatively low-cost manufacturing equipment, the potential for rapid processing is another commercial advantage of RTR production using low-mass substrates such as thin stainless foil. Challenges include the design of robust sensors and *in-situ*, real-time process control strategies. The latter are a prerequisite to viable material properties and process yields. At the module level the use of conductive, flexible substrates requires innovative interconnection schemes to obtain the desired module characteristics. In addition, from a product reliability perspective light-weight, flexible – foldable or rollable – product designs are more complex than standard glass-based modules.

THIN FILM COATING

Process optimization – e.g., by design of experiment (DOE) – requires reliable processing conditions, which in turn are only attainable if robust sensors and real-time, *in-situ* process control strategies are available. Accurate real-time control of CIGS composition and deposition conditions including Se and Na delivery, developed under the US PVMaT and TFPPP programs, enable production of consistent material over 1000-ft lengths in GSE's RTR process [1-5]. Actual monitored real-time run data for a well-controlled CIGS run is plotted in Figure 1 over 1000-ft of processed web, representing about 17 hours of continuous deposition. The level of control demonstrated for a routine absorber formation run along with advances in process monitoring and control for the remaining TFC steps has enabled GSE to achieve a substantial increase in manufacturing yield and further optimization of cell efficiency. A consequent DOE approach employing well-controlled experiments has been instrumental to a rise in manufacturing yield since mid 2002 from 20% to above 90%, as shown in Figure 2. As evident from Figure 3, the device efficiency distribution has been improved significantly.

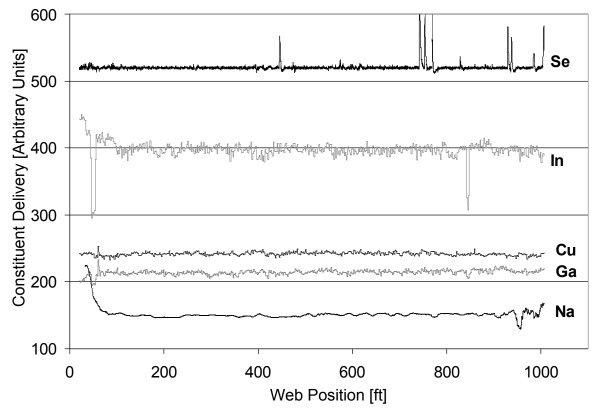

Figure 1. Real-time data taken during a well-controlled 1000-ft run at GSE. The variation in metals thickness is typically less than ± 100 Å during the 17 hour deposition.

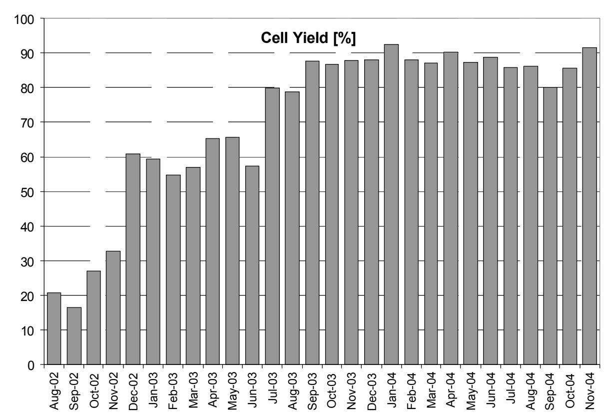

Figure 2. Yield (η > 5.2%) for large-area (68.8 cm^2) production cells at GSE vs. time.

The development of robust processes is another path toward improved control for the production of consistent material. One example, currently a focus of effort at GSE under the US PVMaT program, is the evaluation of robust processes for TCO deposition. The standard process yields TCO whose material properties vary over the course of each run due to several factors, including changing levels of residual contaminants and the evolution of target surface chemistry. Ideally, a robust process would be insensitive to uncontrolled variables, and would produce TCO with very consistent material properties. A robust process under evaluation at GSE is compared to the standard process for a 1000-ft web in Figure 4. Each process is alternately used over the course of the run, showing variation in sheet resistivity for the standard process. In contrast, more consistent and improved TCO sheet resistivity is evident for the robust process.

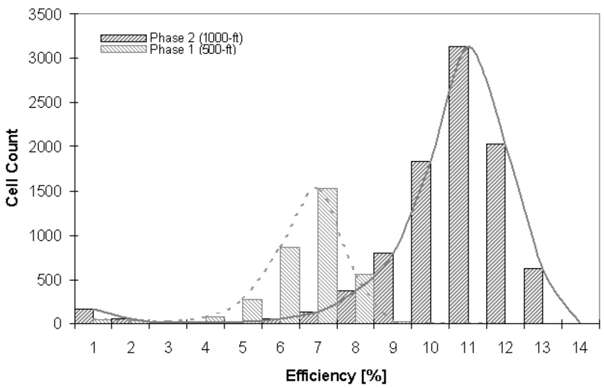

Figure 3. Histograms of cell efficiency for lots of cells before and after campaigns to improve processing control and optimized cell efficiency. Initially, production lots were 500-ft in length, but were increased to 1000-ft as the real-time control capability advanced.

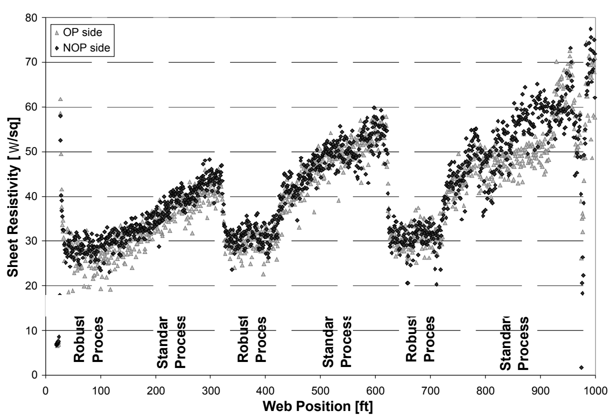

Figure 4. TCO sheet resistivity measured on both sides ("OP" and "NOP") of a 1000-ft CIGS web alternately using either the standard process or a robust process under evaluation.

Global Solar has also used the accelerated process development capability to successfully double the processing speed for the absorber deposition without sacrificing device performance or process yield. The histogram in Figure 5 compares devices based on GSE's previous absorber deposition process at 6-in/min to those based on a 12-in/min process. Despite reducing the total time for CIGS metals deposition to less than 5 minutes, the fast process could be optimized to maintain both good device performance and excellent yield. Buffer layer formation has also been accelerated by a factor of 1.5 and optimized without negative impact on either device performance or process yield (Figure 6).

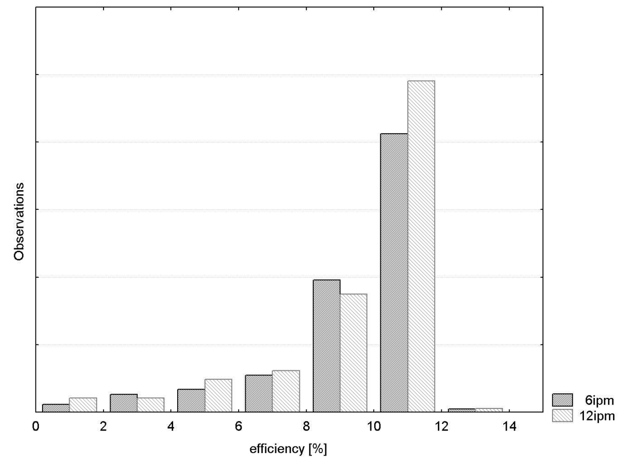

Figure 5. Histogram of cell efficiency, showing a two-fold increase in absorber formation rate with no impact on cell yield, distribution or average efficiency.

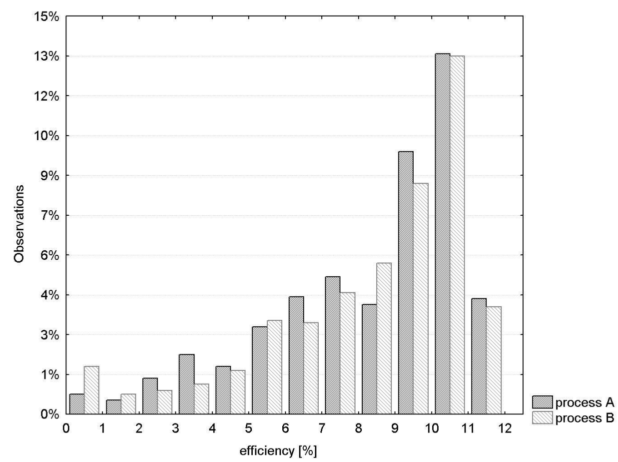

Figure 6. Large area device and yield distribution for previous CdS process (A) and new process (B) using a deposition rate increased by a factor of 1.5×.

LIGHT-WEIGHT FLEXIBLE MODULES

Improved fabrication methods resulted in increased efficiency and yield at the module level. GSE's current flexible module technology employs strings of large area cells connected in series via a cell overlap method, also referred to as shingling. However, electrical shunts can easily form at the exposed edge of the stainless foil substrate of the overlapped cell, reducing module efficiency. GSE has developed a cell integration process to avoid the problem. As illustrated in Figure 7, optimization of this process (B) at the cell level demonstrated a statistically significant improvement at the

95% confidence level over the previous process (A).

The combination of all process improvements at both the thin film coating and the cell generation level routinely yields devices above the 12% conversion efficiency level. Light I-V parameters of a representative example are summarized in Table 1. Although the improvements cited have not yet been fully implemented into the manufacturing area, some existing GSE product designs have already demonstrated a power-to-weight ratio of 40W/kg and aperture area efficiencies exceeding 11% in a flexible product (Table 1). Also listed in Table 1 are NREL verified I-V parameters of a representative module from GSE's SlimLine product, a semi-rigid design. As the proportion of large area devices above 12% efficiency increases, new and existing products will be introduced to the market at still higher power-to-weight ratios.

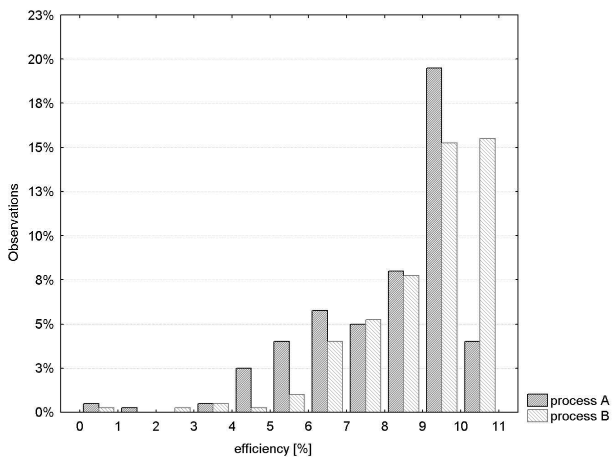

Figure 7. Histogram of large-area cell efficiency with and without modifications during cell generation to protect cell edges linked to shunt generation in modules.

Table 1. Production cell and module I-V characteristics. [(1)] NREL verified measurement.

	Total Area	Aperture Area	
	Cell	P3	SlimLine[(1)]
V_{max} [V]	0.455	27.00	42.11
I_{max} [A]	1.992	1.61	1.69
P_{max} [W]	0.906	43.38	71.21
V_{oc} [V]	0.607	35.01	57.47
I_{sc} [A]	2.347	1.90	2.01
FF [%]	63.67	65.28	61.50
η [%]	13.17	11.13	10.10
Area [cm^2]	68.80	3898	7085

Product attributes such as high flexibility and low weight are integral parts of all GSE products. However, the modules need to be rugged in order to reliably provide power under the harshest of outdoor deployment conditions. Suitable polymer-based encapsulants and adhesives for use in a truly flexible and lightweight PV module are under investigation in both real-time and accelerated test environments. Data is compared to controls encapsulated in glass. Although the UL1703 required accelerated test protocols, such as 1000h at 85°C and 85% relative humidity (DH-1000), may not have direct correlation to outdoor performance, they nonetheless yield important information as to failure mechanisms under those conditions.

Studies of water vapor ingress into polymer-based encapsulation structures revealed no effective protection even for multilayered structures of various laminates. Apart from glass/glass laminated test samples, which were stable, moisture break through in the all-polymer specimens occurred after relatively brief periods in a damp heat (85/85) environment. One approach followed by various private enterprises and research laboratories is to develop high moisture barrier materials for effective protection of the PV layer from climatic influence through complex inorganic or hybrid polymer (multi) coatings [6,7]. An alternate approach, pursued by GSE, is to ensure that the PV itself is insensitive to moisture penetration through the encapsulants. Addressing the problem internally, rather than externally through complex packaging, is highly desirable from an economic perspective, as laminates and adhesives already comprise a substantial portion of the module cost and cannot be further burdened with increased encapsulant costs. Literature data suggests that, with respect to the absorber, stability might be a function of Ga content and thickness [8,9]. As for the TCO layer and front contact grid, 85/85 data generated at GSE so far indicates excellent stability.

To date, several environmental degradation modes with varying time constants have been observed in a variety of polymer-based lamination structures. While the detailed mechanisms are not yet understood in each case, the origins for a number of modes have been identified. One failure mode has been linked to dimensional change in thermally unstable laminates, impacting product reliability. Table 2 lists the relative dimensional change upon lamination for a variety of flexible polymer based laminates in both the transverse and machine direction. Also shown for the case of ETFE is the variation with an increase in temperature at fixed times. Furthermore, renewed subjection to increased temperatures can result in additional dimensional changes for some laminates.

Another aspect that has been explored was grid line reddening upon outdoor deployment or under DH conditions. While no negative impacts on module performance could be observed, grid line reddening nonetheless was perceived as undesirable from an appearance perspective. Careful experimentation lead to the conclusion that a specific chemical incompatibility exists between constituents found in certain laminates with the grid material.

Glass encapsulated control modules have so far demonstrated excellent stability under outdoor and accelerated environmental stress conditions (e.g., DH-1000, TC-200, HF-10) exhibiting losses of only a few percentage points of initial power. Moreover, careful selection, combination and treatment of laminates and adhesives has substantially improved product reliability of all-polymer modules to within a few percent of the glass reference.

Table 2. Dimensional changes [%] for various laminates at lamination times and temperatures.

sample	transverse direction		machine direction	
	average	± 1σ	average	± 1σ
TUF	-0.04	0.50	0.36	0.44
Quadlam.	-0.08	0.14	-0.58	0.14
PET	-0.36	0.20	-0.60	0.33
Nylon - A	-0.25	0.31	-0.97	0.20
PET Fabric	-1.09	0.20	-0.83	0.26
Nylon - B	-1.50	0.22	-1.16	0.23
PVC - A	1.73	0.17	-5.28	0.39
PVC - B	3.03	0.11	-7.48	0.70
THV	-3.08	2.31	-11.54	7.25
ETFE T_{low}	-0.45	0.27	-2.44	0.17
ETFE $T_{med.}$	-0.78	0.44	-2.61	0.14
ETFE T_{high}	-1.11	0.34	-3.00	0.29

A transient common to the CIGS TF technology is relaxation of the module upon prolonged dark storage resulting in the need to light soak in order to restore module FF and power [10,11]. While the exact mechanism – time characteristics, range of beneficial wavelength, and dose of irradiation required to restore performance – is not yet known, GSE has observed that relaxation in the dark is rapid at elevated temperatures. This effect poses a significant problem under present UL and IEC test protocols, and has implications for test procedures after lamination at elevated temperatures.

In addition to environmental stresses (T and UV), rolling and folding induces mechanical stress on the PV strings and interconnects. Interconnecting methods for flexible modules have been developed at GSE that show excellent mechanical reliability in fatigue tests for current product types and for several new combinations of module construction techniques and materials.

CONCLUSIONS

GSE has achieved consistent material over 1000-ft long metal foil substrates at high throughput in roll-to-roll manufacturing. Well-controlled processes have been realized through the development of robust sensors, processes and *in-situ*, real-time process control strategies for all thin-film coating steps. This capability in conjunction with designed experiments have accelerated device optimization and yield improvement, enabling manufacturing yields above 90% with average large-area cell efficiency exceeding 10%. Module efficiency has also been increased through improved fabrication methods with flexible modules featuring a power-to-weight ratio of 40W/kg and aperture area efficiencies exceeding 11%. Several failure modes for flexible modules have been identified and eliminated through reliability studies using accelerated and real-time testing which is ongoing.

ACKNOWLEDGEMENTS

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